Arctic Sea Ice Model Sensitivities

Kara Peterson (kjpeter@sandia.gov), Pavel Bochev (pbboche@sandia.gov), Biliana Paskaleva (bpaska@sandia.gov)
Sandia National Laboratories

C43E-0604

Introduction

Arctic sea ice is an important component of the global climate system, reflecting a significant amount of solar radiation, insulating the ocean from the atmosphere, and influencing ocean circulation by modifying the salinity of the upper ocean. Due to feedback effects, changes in the Arctic sea ice cover are accelerating and predictive mathematical models are essential for accurate estimates of the future ice trajectory.

Sea ice components of Global Climate Models (GCMs) vary significantly in their predictions for the future state of Arctic sea ice and have all underestimated the rate of decline in minimum sea ice extent over the last thirty years. Additionally, the dynamic predictions of sea ice models differ substantially from model to model. An important component of this variability is due to uncertainty in model physical parameters. Therefore, an understanding of the sensitivity of the model outputs to various physical parameters is needed to further increase their accuracy and deliver predictive estimates of the future evolution of Arctic sea ice.

Thickness variations in the ice. Source: alaska.usgs.gov.

A new sea ice model has been developed for basin-scale calculations of the Arctic ocean that combines an anisotropic rheology with a particle-in-cell type numerical solution of the ice dynamics governing equations. The anisotropic rheology more realistically captures sea ice deformation and the Lagrangian particles naturally handle advection. We compare this model to the LANL CICE code for one year simulations of the Arctic basin where ten physical parameters common to both codes are varied.

Sea Ice Governing Equations with Sensitivity Parameters Highlighted in Red

2-D momentum equation for ice velocity ($\mathbf{v}$):

$$\rho\bar{h}\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = \nabla\cdot(\bar{h}\sigma) + \mathbf{t}_a + \mathbf{t}_w - \mathbf{f}_c$$

Coriolis Force: $\mathbf{f}_c = 2\rho\bar{h}\omega\sin\phi(e_3\times\mathbf{v})$
Atmospheric Drag: $\mathbf{t}_a = c_a\|\mathbf{v}_a\|\mathbf{v}_a$
Ocean Drag: $\mathbf{t}_w = c_w\|\mathbf{v}-\mathbf{v}_w\|(\mathbf{v}-\mathbf{v}_w)$
Stress: σ from rheology

Ice thickness distribution (g) for variations in thickness (h):

$$\frac{\partial g}{\partial t} + \nabla\cdot(\mathbf{v}g) + \frac{\partial(fg)}{\partial h} = \psi$$

Average thickness: $\bar{h} = \int_0^\infty hg\,dh$
Redistribution function: $\psi(\mu, a^*)$

1-D heat equation for temperature (T) and thickness change ($f = \partial h/\partial t$) due to growth and melt:

$$\rho c(S,T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k(S,T)\frac{\partial T}{\partial z}\right) + \kappa I_0 e^{-\kappa z}$$

Flux balance at ocean: $F_w - k(S,T)\frac{\partial T}{\partial z} = -q(S,T)\frac{\partial h}{\partial t}$
Flux balance at atmosphere: $F_R(1-\alpha) - I_0 + F_L - \epsilon\sigma T_0^4 + F_s + F_l + k(S,T)\frac{\partial T}{\partial z} = -q(S,T)\frac{dh}{dt}$

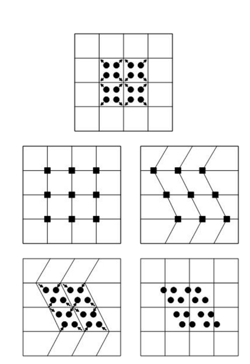
Salinity: $S(z) = \frac{1}{2}S_{max}(1 - cos(\pi z^{\frac{a}{z+b}}))$
Albedo: $\alpha(T, h, \alpha_{ice,v}, \alpha_{ice,i}, \alpha_{snow_v})$

Conductivity: $k(S,T) = k_0 + \frac{\beta S(z)}{T}$
Shortwave radiation transmitted: $I_0 = i_0 F_R(1-\alpha)$

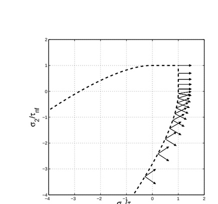
Model Configuration

MPM Sea Ice Model [6]

- Horizontal discretization - Material-Point Method (MPM)
  - Domain divided into material points and background grid
  - Lagrangian material points carry mass, momentum, thickness distribution, and internal variables for constitutive model
  - Momentum equation solved on background grid using FEM
- Elastic-decohesive rheology [4]
  - Leads modeled as displacement discontinuities
  - Intact ice modeled as elastic
  - Predicts initiation and orientation of lead
- Energy conserving thermodynamics
- Multi-level ice thickness distribution (5 thickness categories for sensitivity simulations)
- Temperature and thickness dependent albedo parameterization



MPM algorithm steps.

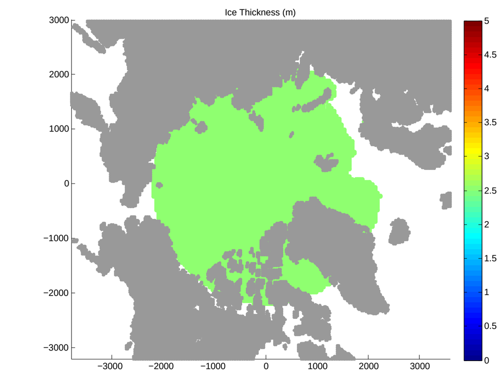


Elastic-decohesive failure curve in principal stress space with stress normalized by tensile failure strength. Arrows indicate normal direction to discontinuity

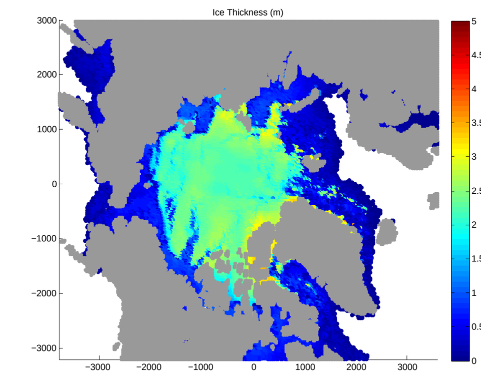
LANL CICE Model [2]

- Horizontal discretization on B-grid
- Linear remapping for advection
- Elastic-viscous-plastic rheology
- Energy conserving thermodynamics
- Multi-level ice thickness distribution
- Temperature and thickness dependent albedo parameterization

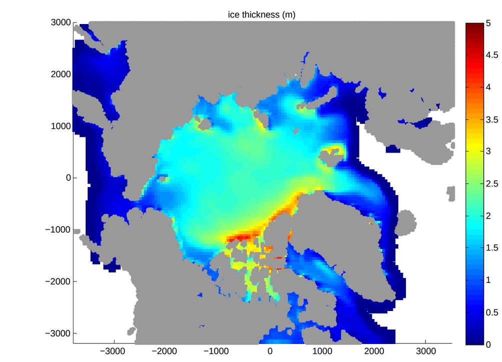
Pan-Arctic Simulations



Ice thickness, initial configuration.



MPM December ice thickness for nominal parameter values.



CICE December ice thickness for nominal parameter values.

The simulations were performed at 50 km resolution on a rectangular grid (azimuthal equal area projection). The sea ice was initialized with a uniform ice thickness distribution for regions above 70 degrees N latitude with SST less than the freezing temperature of sea ice. Atmospheric data from the CORE 2 [3] and ocean data from PIOMAS [7] for 1997 are used to drive the calculations.

Parameters and Response Functions

Parameters were chosen based on their impact in previous sensitivity studies and their common inclusion in both the CICE and MPM sea ice models. Response functions were chosen for their importance in assessing the state of the Arctic ice pack.

Table: Model Parameters.

Parameter	Nominal Value	Range	Description
$\alpha_{ice,v}$	**0.78**	0.7-0.86	Visual ice albedo
$\alpha_{ice,i}$	**0.36**	0.32-0.4	Near-infrared ice albedo
$\alpha_{snow,v}$	**0.98**	0.88-1.0	Visual snow albedo
ϵ	**0.95**	0.85-1.0	Emissivity
i_0	**0.70**	0.63-0.77	Fraction of shortwave radiation penetrating ice
k_0	**2.03**	1.827-2.233	Fresh ice conductivity ($W/(mK)$)
S_{max}	**3.2**	2.88-3.52	Maximum salinity (ppt)
c_w	**0.0055**	.00495-.00605	Ice-ocean drag parameter
a^*	**0.05**	0.045-0.055	Ridging parameter
μ	**4**	3.6-4.4	Ridging parameter

Table: Response Functions.

Variable	Description
A_{tot}	Total ice area (km^2)
E_{tot}	Total ice extent (km^2)
V_{tot}	Total ice volume (m^3)
$\mathbf{v}_{rms}$	RMS ice speed (m/s)
h_{CA}	Central Arctic ice thickness (m)
$\mathbf{v}_{CA}$	Central Arctic ice speed(m/s)

Sensitivity Methodology

The sensitivity analysis was performed with the DAKOTA toolkit [1], in which 50 Latin Hypercube Samples (LHS) were taken. The analysis used a linear regression model. Given responses y_i for $i = 1, \ldots, 50$ input values and instantiations of the parameters x_{ij} ($j = 1, \ldots 10$) for each sample, the model can be algebraically formulated as

$$(y - \bar{y})/\hat{s} = \sum_j \frac{(a_j\hat{s}_j/\hat{s})(x_j - \bar{x}_j)}{\hat{s}_j},$$

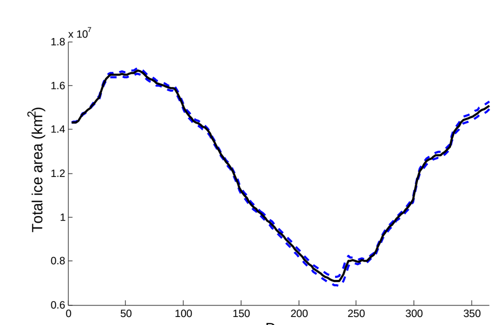
where

$$\bar{y} = \sum_i \frac{y_i}{m}, \hat{s} = \left(\sum_i \frac{(y_i - \bar{y})^2}{(m-1)}\right)^{1/2}, \qquad \bar{x}_j = \sum_i \frac{x_{ij}}{m}, \hat{s}_j = \left(\sum_i \frac{(x_{ij} - \bar{x}_j)^2}{(m-1)}\right)^{1/2}.$$

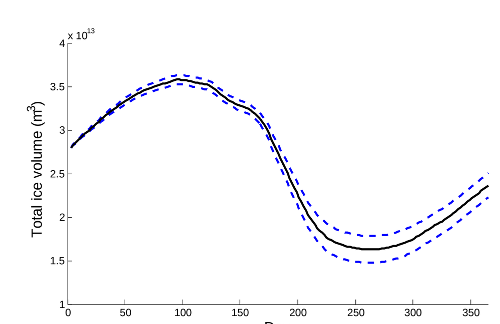
The coefficients $a_j\hat{s}_j/\hat{s}$ are called standardized regression coefficients. Their values are scaled in the range of -1 to 1. When the x_j are independent, the absolute value of the standardized regression coefficients can be used to provide a measure of variable importance with respect to observed uncertainty in the response function.

One Year Cycle for Selected Response Functions

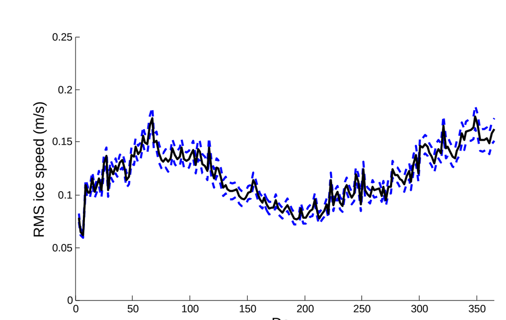
Black line is mean of 50 LHS and blue lines are the $\pm 2\sigma$ bounds.



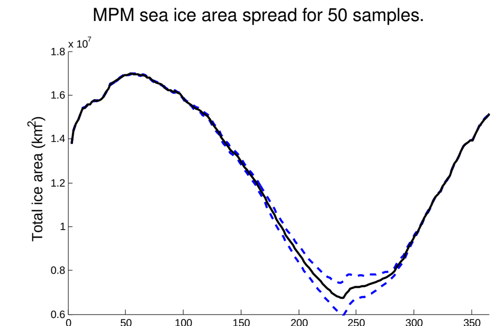
MPM sea ice area spread for 50 samples.



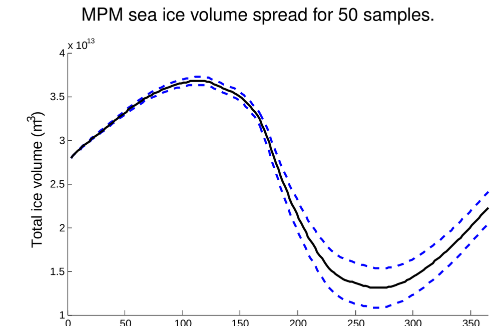
MPM sea ice volume spread for 50 samples.



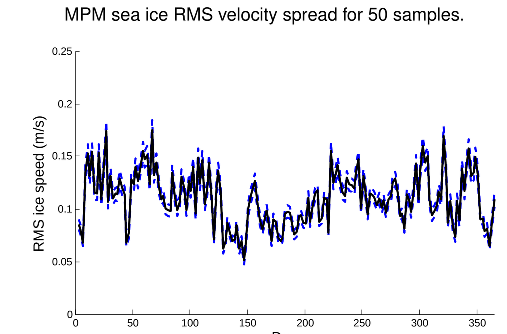
MPM sea ice RMS velocity spread for 50 samples.



CICE sea ice area spread for 50 samples.

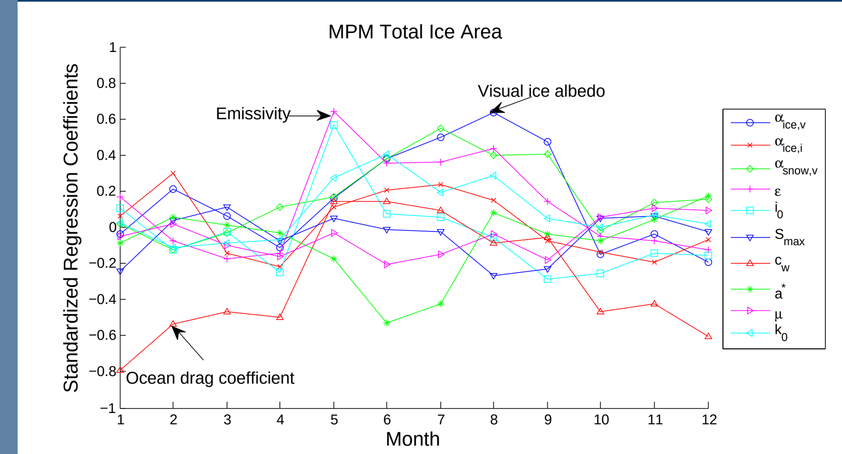


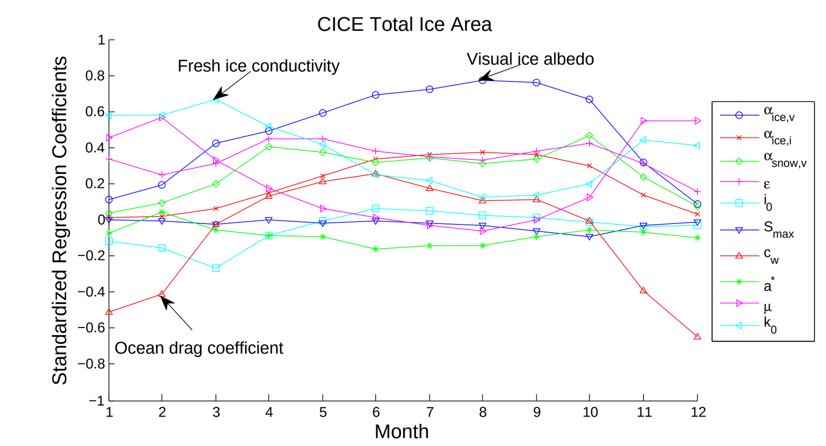
CICE sea ice volume spread for 50 samples.

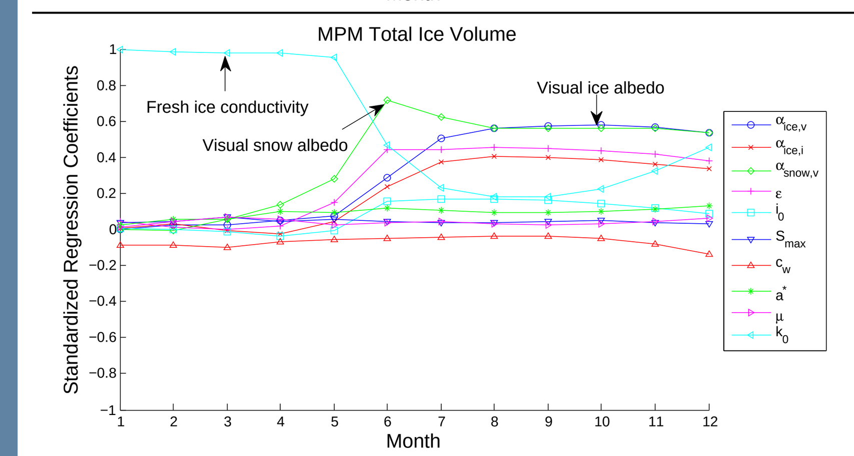


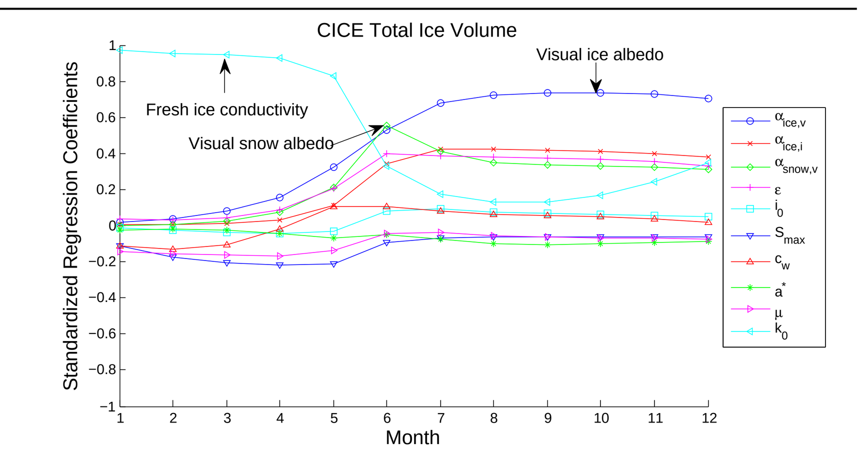
CICE sea ice RMS velocity spread for 50 samples.

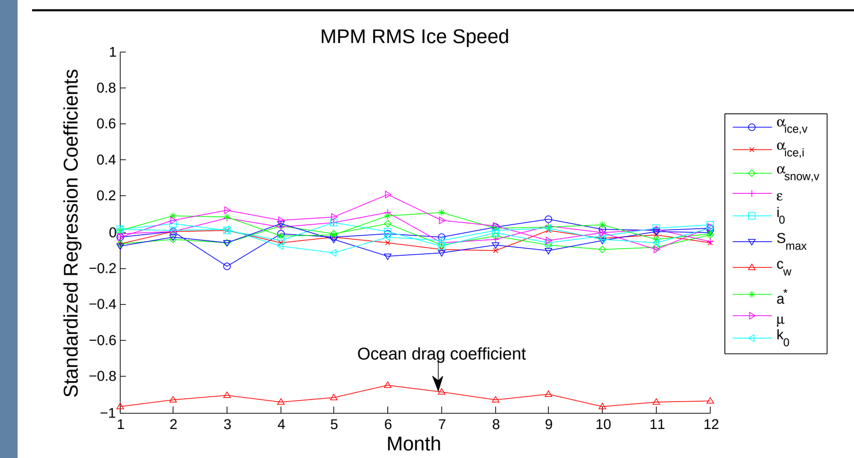
Standardized Regression Coefficients for Selected Response Functions

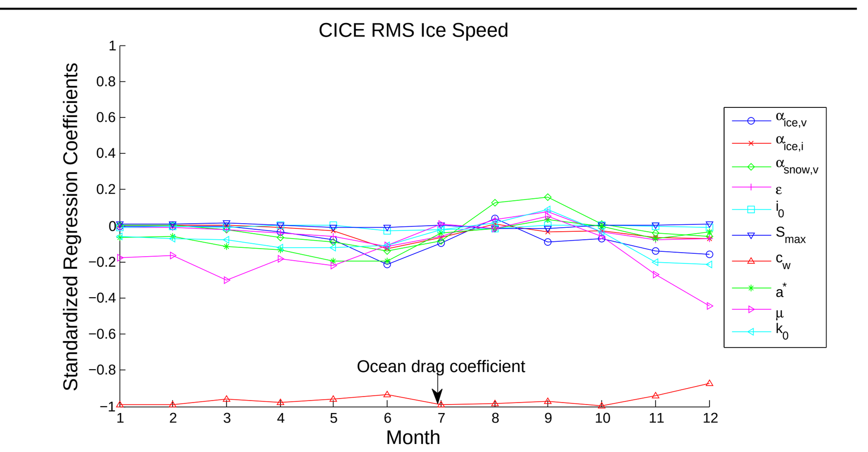












Discussion

Although, the ice thickness distribution and velocity at the end of the one year simulation differ substantially between the codes, the response of each code to perturbations in a set of ten dynamic and thermodynamic parameters is quite similar. Among the six response functions, the total ice area and total ice extent show similar behavior, the total ice volume and central Arctic ice thickness show similar behavior, and the RMS ice speed and central Arctic ice speed show similar behavior. Therefore, only the total ice area, total ice volume, and RMS ice speed results are plotted here.

The total ice area and extent display strong negative sensitivity responses to the ocean drag coefficient (c_w) at the beginning and end of the year corresponding to times where there is a considerable amount of new relatively thin ice that could ridge efficiently under converging conditions. In the middle of the year when melting dominates, the dependence on the ocean drag coefficient is significantly reduced. As expected, thermodynamic parameters become more important during this time as seen in the CICE results, which show a strong positive sensitivity response to visual ice albedo for May through October.

Interestingly, the central Arctic ice thickness and total ice volume show a strong positive response to fresh ice conductivity (k_0) in the first part of the year, but, as expected, the albedo parameters ($\alpha_{ice,v}, \alpha_{ice,i}, \alpha_{snow,v}$) become more significant than the conductivity between May and June.

Unsurprisingly, the RMS ice speed and central Arctic ice speed show strong negative responses to the ice-ocean drag coefficient (c_w). It is notable that no other parameters in this study show much influence on the velocity related response functions.

This analysis is a first step in confirming the dominant parameters in the MPM and CICE models. Further analyses will provide more information on the actual dimension of the problem space for use in the developement of a reliable, computationally efficient, and scalable uncertainty quantification methodology for high-fidelity Arctic sea ice models.

Acknowledgements

Funding from the Laboratory Directed Research and Development program is gratefully acknowledged.

References

[1] B. M. Adams, W. J. Bohnhoff, K. R. Dalbey, J. P. Eddy, M. S. Eldred, D. M. Gay, K. Haskell, P. D. Hough, and L. P. Swiler. DAKOTA, a multilevel parallel object-oriented framework for design optimization, parameter estimation, uncertainty quantification, and sensitivity analysis: Version 5.0 user's manual. Technical Report SAND2010-2183, Sandia National Laboratories, 2009.

[2] E. C. Hunke and W. H. Lipscomb. CICE: the Los Alamos sea ice model documentation and software user's manual version 4.0. Technical report, LANL, 2008.

[3] W. G. Large and S. G. Yeager. The global climatology of an interannually varying air-sea flux data set. *Climate Dynamics*, 2008.

[4] H. Schreyer, L. Monday, D. Sulsky, M. Coon, and R. Kwok. Elastic-decohesive constitutive model for sea ice. *Journal of Geophysical Research*, 111:C11S26, 2006.

[5] D. Sulsky and K. Peterson. Towards a new model of Arctic sea ice. *Physica D*, submitted, 2010.

[6] D. Sulsky, H. Schreyer, K. Peterson, M. Coon, and R. Kwok. Using the material-point method to model sea ice dynamics. *Journal of Geophysical Research*, 112:C02S90, 2007.

[7] J. Zhang and D. A. Rothrock. Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates. *Monthly Weather Review*, 131(5):681–697, 2003.

Sandia is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the U. S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.